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13. ABSTRACT (Maximum 200 words)

SRI investigated ways to harvest otherwise wasted energy from walking. The recovered energy, potentially on the order of 1-2 W per boot, can be used by a soldier to supplement battery power, as an emergency backup source of power, for specialized on-board boot functions such as inertia navigation, and, in the future, to enhance walking and other mobility performance. The approach used by SRI was electroactive polymers (EAP's), rubbery materials that generate electrical power when stretched and contracted. There were five major results of the project including (1) demonstration that non-piezo EAP's can be used as powerful generator materials and development of supporting theory and experiment, (2) development and demonstration of boot generators capable of generating up to 0.8 J/step of energy, (3) development of several mechanical boot generator designs and their associated EAP fabrication techniques, (4) development of boot generator electronics and identification of areas for future work needed for miniaturization, and (5) technology transfer including a follow-on project with a manufacturer to develop a commercial product.

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HEEL-STRIKE GENERATOR USING ELECTROSTRICTIVE POLYMERS

ITAD-3494-FR-02-123
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Heel-Strike Generator Using Electrostrictive Polymers

SRI International (SRI) is pleased to submit this final report, ITAD-3494-FR-02-123, SRI project EMU 3494, Heel-Strike Generator using Electrostrictive Polymers, to the Army Research Office (ARO) and Defense Advanced Research Projects Agency (DARPA).

1 STATEMENT OF THE PROBLEM STUDIED

SRI investigated ways to harvest otherwise wasted energy from walking. The recovered energy, potentially on the order of 1–2 W per boot, can be used by a solder to supplement battery power, as an emergency backup source of power, for specialized on-board boot functions such as inertia navigation, and, in the future, to enhance walking and other mobility performance. The approach used by SRI exploited electroactive polymers (EAPs), rubbery materials that generate electrical power when stretched and contracted.

2 SUMMARY OF THE MOST IMPORTANT RESULTS

The project produced several important results. First and perhaps foremost for future DoD applications, we demonstrated that electroactive polymers can function as powerful generator materials. Prior to this project, electroactive polymers (non-piezoelectric) had been investigated by SRI and others only as actuator materials. Their use for generator functions was only theoretical at the start of the project, but we showed that certain polymers, such as acrylic elastomers, were amongst the most powerful generator materials known, particularly in terms of generated energy output per unit weight of material. Generator energy densities as high as 0.4 J/g were recorded, a value we believe, based on the available literature, to be the highest ever recorded. In addition to our experimental work, we developed and tested the theory of operation of the EAPs as generator materials, and showed that good agreement existed between theory and experiment. This fundamental work in EAP generator materials and systems is a valuable legacy of the project because it will enable other DoD applications to be developed from a solid theoretical and experimental foundation. Indeed, work is already in progress on novel DoD applications in which electroactive polymers are used for integrated polymer engine-generators.

A second important result of the project was the demonstration of good output, up to 0.8 J/step, in a heel-strike generator. At the start of the project, the state of the art in shoe generators produced output measured in a few tens of millijoules at best. Thus, the project showed that attractive levels of power from boot generators can be achieved with compact, lightweight polymers that are low cost and well suited for boots (unlike, for example, brittle ceramic piezoelectrics).

A third important result of the project was the development and testing of various mechanical designs for the heel-generator. These included diaphragm and contour-based stretching (CBS) designs (see Figure 1), with numerous variations within those general classes. Heel-strike diaphragm generators with up to 20 layers of EAP were successfully demonstrated. Although these diaphragm devices achieved good performance, leakage of the oil used to hydraulically stretch the diaphragms during heel-strike was problematic. More recently, SRI successfully demonstrated the use of a soft gel instead of oil as the hydraulic medium. This approach appears promising for future heel-strike generators, particularly because soft gels are already used in some commercial shoe pads.

Diaphragm devices were also used to demonstrate the good durability of the generator. Although durability was initially a problem, we demonstrated diaphragms in more than 32 hours of continuous operation. Good durability is achievable if the generator is operated within certain strain-voltage constraints. Less testing was done with the CBS designs, but CBS generators also gave good energy output, comparable to that of diaphragm devices. The CBS generators were very lightweight because they did not include oil and bellows. However, less is known about their durability and stress concentrations from the stretching surfaces may be an issue.

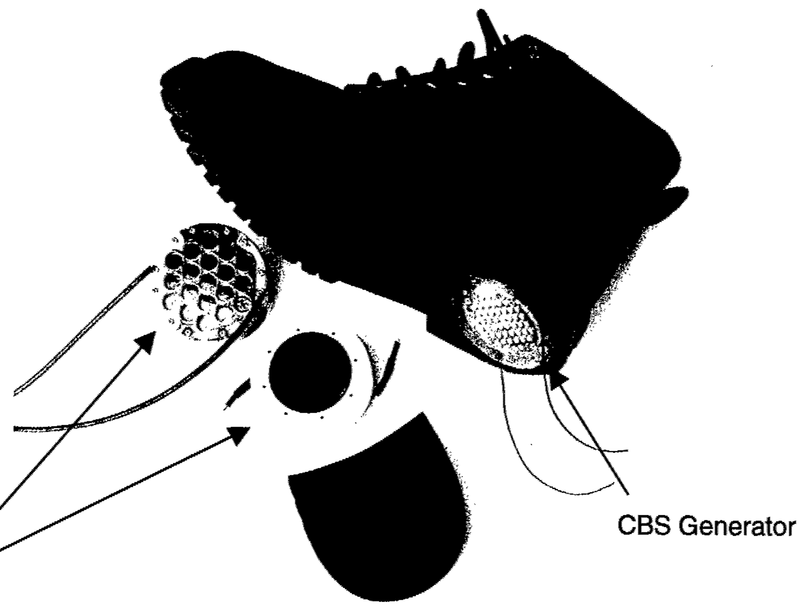

Figure 1. Diaphragm and CBS Boot Generators

A fourth major result of the project was in the area of electronics. The boot generator requires the initial generation and manipulation of high voltage, and because most applications require low voltage output, the generator electronics must also step down the high voltage output by the EAP. We successfully addressed the initial generation of high voltages by using a number of techniques such as charge pumping. We also demonstrated efficient (70–80%) step-down of high voltage but not, unfortunately, in a heel-size circuit. The step-down problem was traced to the lack of commercially available low-power, high-voltage transistors. Although the transistor problem was not fully addressed in the project, discussions with transistor companies showed that the problem was not fundamental; instead, the lack of appropriate transistors merely reflected current transistor markets. It should therefore be feasible in future work on EAP boot generators to obtain custom-built low-power, high-voltage transistors that can be used to make heel-size electronics for the generator.

Lastly, we note that work on this project has been successfully transitioned to the next stage of development. SRI is currently working closely with a commercial manufacturer to solve the remaining technical and manufacturing issues with the goal of developing a commercial product.

3 PUBLICATIONS

Pelrine, R., R. Kornbluh, J. Eckerle, P. Jeuck, S. Oh, Q. Pei, and S. Stanford. 2001. "Dielectric Elastomers: Generator Mode Fundamentals and Applications," in *Smart Structures and Materials 2001: Electroactive Polymer Actuators and Devices*, Yoseph Bar-Cohen, Editor, Proc. SPIE, vol. 4329, pp. 148–156 (non-peer-reviewed).

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5 REPORT OF INVENTIONS BY TITLE

1. "Methods to Improve Electroactive Dielectric Elastomers"
2. "Laminates for Enhanced Electromechanical Performance of Field-Activated EAP's"
3. "Bellows/Trapped Fluid/Grid Plate for Muscle Coupling"
4. "Generator Power Conversion Circuit"
5. "Smarter Shoes and Sportswear"
6. "Dynamically Self-Adjusting Footware Using Fluid Transmission"
7. "Muscle Transmission and Various Shoe-Related EPAM Concepts"
8. "Conformal Based Stretching (CBS) Chamber for An EPAM Generator."